

Cluster Combustion of Binary-Fuel Drops

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1 Introduction

Most fuels used in practical combustion liquid-fuel sprays devices are blends of several components. In many cases, the composition of the fuel is considered critical for the operation of the device due to efficiency and pollution production considerations. These concerns have motivated during the last two decades a substantial number of studies addressing the problem of single, isolated drop evaporation, ignition and combustion. While these studies have contributed important understanding of the physics of the internal drop processes and their coupling to the flow surrounding the drop, they have not directly addressed the realistic situation of drop interactions in a spray and the consequences that these have upon the internal drop processes. Experimental evidence [1],[2], [3], [4],[5],[6] shows that sprays do not burn with individual drop flames; instead, there is a multitude of flames, each flame surrounding a group of drops which is called here a cluster of drops. These cluster flames are an important indication of drop interactions.

This investigation focuses on cluster flames for binary-fuel drops. A binary-fuel is a practical representation of typical fuels often composed of hundreds of pure fuels. Since this study is done in the context of alternate fuels, the solvent represents the viscous, nonvolatile fractions whereas the solute represents the low-viscosity, volatile fractions.

2 Description of the Model

The configuration studied is that of a spherical cluster of relatively cold spherical drops exposed to an axial flow at a higher temperature. The drops also move radially inside the cluster with respect to the cluster center and this motion is assumed to be self-similar [7]. The mathematical model is based upon the formulation of [8] for evaporation of binary-fuel drops in clusters, upon the formulation of ignition of clusters of binary-fuel drops of [9], and upon the formulation for single-component fuel cluster-combustion of [10] which has been adapted here for binary-fuel drops. One conclusion of [10] is that cluster flames exist only in a restricted range of air/fuel mass ratios, Φ 's. This is because if Φ is very small, the cluster may be so dense that the drops extract too much heat from the gas during evaporation, before heat transfer processes from the cluster surroundings may replenish it, and thus the temperature becomes too low to initiate ignition. For these clusters, evaporation proceeds without ignition until the drops disappear. Ignition might occur later in the gas phase, but this situation is outside the focus of this study. When Φ is very large at ignition, the gaseous mixture inside the cluster is fuel-lean and internal cluster combustion [10] depletes all gaseous fuel inside the cluster. With no gaseous fuel left to escape the cluster, the external cluster

flame cannot become established. These two situations represent the lower and upper limits for the existence of cluster flames. Thus, cluster flames exist for clusters which are not too dense (so that cluster ignition may occur) and for which the gaseous mixture is fuel-rich at ignition.

During evaporation, the composition of the gas inside the cluster is determined by the evaporation of the two fuels and by the transport of fuel across the moving cluster boundary. The boundary conditions at the cluster surface have been described in [11]; the model used here is that described by the formulation called "strong turbulence" (model 2). Cooling of the gas inside the cluster due to drop evaporation induces cluster contraction whereas heating of the gas inside the cluster through heat transfer from the cluster surroundings induces cluster expansion and engulfing of the surrounding cluster gas. It is thus the competition between these two processes which determines the motion of the cluster boundary, the cluster gas composition and its temperature. Solvent and solute evaporate from the drop at rates determined by the internal drop and drop-surface processes as explained in [8]. If the relative velocity at the drop surface, u_s , is negligible so that there is no shear and therefore no induced circulatory motion inside the drop, the solute evaporates at the same rate as the solvent, and this has been termed surface layer stripping [8]. In contrast, if the relative velocity at the drop surface is strong enough to induce circulation inside the drop, liquid mass diffusion becomes an important process and preferentially enhances evaporation of the solute. Then the mass fraction of the solute will decrease inside the drop. The relative velocity between drops and gas is the solution of the momentum equations. The relative importance of liquid mass diffusion and surface layer stripping is quantified by a number $Be \equiv -[R/(D_m u_l)]^{0.5} dR/dt$ where R is the drop radius, D_m is the liquid mass diffusivity, u_l is the liquid circulatory velocity inside the drop, and t is the time. If $Be \ll 1$, liquid mass diffusion controls the process and if $Be \gg 1$, surface layer stripping controls the process. As shown in [8], u_l is a function of u_s .

Ignition may be initiated by either solvent or solute according to the Damköhler number criterion described in [9]. The internal flash flame following ignition [10] burns all of the oxygen inside the cluster; the oxygen is apportioned between solvent and solute according to their average mass fractions at ignition. Following the flash flame there is a flame surrounding the entire cluster, similar to those observed experimentally. The general location of the flame (individual, collective or intermediary internal cluster flame) is calculated at ignition according to a criterion already used in [12]; for the situations studied here the flame is always of the collective type. The location of the flame during collective burning is calculated from the conservation equations.

3 Discussion of Results

The initial conditions specify Φ^0 the initial drop radius, R_c^0 , the initial cluster velocity, u_c^0 , the initial mass fraction of the solute in the liquid, Y_{VL}^0 , the interstitial initial gas temperature inside the cluster, T_{ga}^0 , which is assumed to be the same as the surrounding gas temperature, the interstitial initial composition of the cluster gas which is assumed to be the same as that of the gas surrounding the cluster, the initial drop temperature, T_s^0 , the cluster radius, R_c^0 , the activation energy, E_{ign} , and the preexponential constant, A_{ign} , used in the Damköhler number criterion for ignition and assumed here to be identical for solvent and solute, the pressure (1 atm) and the thermophysical and thermochemical properties of the fuels. The initial conditions for which external cluster flames exist correspond here to the dense cluster regime as defined in [8], or the moderately-dense cluster regime in which the nondimensional radius of the sphere of influence [8] is slightly larger than that in the dense regime. The gas inside the cluster is initially at rest; as the drops move, they entrain the gas which acquires a velocity of its own. The situations studied are all identified in Table 1 and the symbols correspond to those in the figures.

Figures 1, 2 and 3 display the fractions of solvent and of solute burnt in the flash flame following ignition and their ratio. The fractions are increasing functions of Φ^0 because although for larger Φ^0 's ignition occurs earlier in the drop lifetime, there is more oxygen inside the cluster and thus more of the fuel can burn. Note that the ratio of the fractions is always smaller than $Y_{VL}^0/(1 - Y_{VL}^0)$ and is constant with Φ^0 . The reason for this is the initially larger relative velocity at the drop surface which preferentially evaporates the solute (this is the $Be \ll 1$ regime). As a result, Y_{VL} decreases. Since u_s decreases because of drag effects, eventually $Be \gg 1$. Then the preferential evaporation of the solute ceases and the solute evaporates at the rate of the solvent, that is at the frozen rate of the mass fraction when Be became $\gg 1$. This physical picture is the result of examining Be and the fractional evaporation rate of the solute, \dot{m}_v/\dot{m} , versus the residual drop radius, RI . Additionally, this is confirmed by results showing that the ratio of the flash flame burn fractions is a decreasing function of u_c^0 . This ratio increases with Y_{VL}^0 , has a negligible dependence upon the solvent identity and is independent upon the solute identity. The fact that this ratio is always smaller than $Y_{VL}^0/(1 - Y_{VL}^0)$ indicates that eventually there is a steady-state situation that establishes where the amount of fuel escaping through the cluster boundary balances that evaporating from the drops.

Plots of the respective ratios (all at $R_1 = 0.05$) of the burned fraction during external cluster combustion to the fraction that escaped the cluster for solvent, $\dot{f}_{b,s}/\dot{f}_{loss,s}$, and for solute, $\dot{f}_{b,v}/\dot{f}_{loss,v}$, depicted in Figs. 4 and 5 show two types of behavior. Strong flames that are established further away from the cluster surface (see Fig. 6 displaying the nondimensional distance from flame to cluster) are encountered for smaller Φ^0 's and for larger u_c^0 's. In this case, it is only a small fraction of the fuel release from the cluster that is burned by the time of drop disappearance. For large u_c^0 's, the small evaporation rate at the end of the drop lifetime can no longer sustain the strong flame and instead of burning, extinction occurs. Mathematically, extinction is identified when the integrated consumption rate at the flame decreases instead of increasing with time. This means that a quasi-steady flame can no longer be maintained; it is possible that an unsteady flame could still exist under these conditions. Weak flames are established extremely close to the cluster surface; they occur mainly for large Φ^0 's and small u_c^0 's. These flames behave asymptotically like classical quasi-steady diffusion flames where the fuel emitted by the cluster is almost entirely burnt in the flame ($\dot{f}_{b,s}/\dot{f}_{loss,s}$ and $\dot{f}_{b,v}/\dot{f}_{loss,v}$ are nearly 1). For intermediary values of u_c^0 , the classical behavior of the diffusion flame is never reached, indicating the importance of convective effects. Note that $\dot{f}_{b,v}/\dot{f}_{loss,v} \geq \dot{f}_{b,s}/\dot{f}_{loss,s}$, with the equality occurring for weak diffusion flames. In that case, convective effects which preferentially evaporate the solute are not important. Examination of $\dot{f}_{loss,v}/\dot{f}_{loss,s}$ shows that it is only very slightly increasing function of Φ^0 and depends mainly upon Y_{VL}^0 and u_c^0 . This ratio depends only slightly upon solvent identity and does not depend upon solute identity. A similar comment applies to $\dot{f}_{b,v}/\dot{f}_{b,s}$, except that instead of it being a slightly increasing function of Φ^0 it is a slightly decreasing function of Φ^0 . Thus, although proportionally less solute is released from the cluster for small Φ^0 , proportionally a larger fraction of solute is burned. The situation where extinction is obtained represents an exception, as both ratios are increasing functions of Φ^0 .

For diffusion-dominated combustion, the fraction of fuel burnt during combustion is an increasing function of Φ^0 because ignition occurs earlier during the drop lifetime. As convective effects become important, the flame is relatively stronger in the small Φ^0 regime than in the purely diffusion regime as evidenced by the slope of the nondimensional flame distance to the cluster surface; as a result, it burns a larger fraction of fuel. Thus, for intermediary convective combustion, the fuel fraction burned during combustion is a nonmonotonic function of Φ^0 , and convex. When convection dominates, the flame is considerably stronger for small Φ^0 's and accordingly an increasing fuel

fraction is burned. The total fraction of fuel burned (flash flame and combustion) is an increasing function of Φ^0 since the later ignition for small Φ^0 's also corresponds to situations where there is less oxygen inside the cluster and thus less fuel may be consumed by the flash flame.

Changing the ignition kinetics translates and enlarges or shrinks the collective flame regime on the Φ^0 axis but does not change the results qualitatively.

4 Summary and Conclusions

A model of binary-fuel drop combustion with collective cluster flame has been formulated. This regime is not encountered for clusters that are too dense to ignite while there are still drops present, or for clusters where the gas phase is lean at ignition. It turns out that this regime corresponds to the dense cluster regime. Results obtained with this model show that even in the dense regime (as distinct from the very dense cluster regime), drop interactions are important in modifying the fraction of fuel burned. The influence of the convective effects, the fuel composition and the ignition kinetics in the Damköhler number criterion have also been investigated.

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Table 1 Parameters used in the study and corresponding symbols in figures

	solvent	solute	u_c^0 , cm/s	Y_{VL}^0	E_{ign} , kcal/mole
+	n-decane	n-hexane	20	0.2	30
□	n-decane	n-hexane	80	0.2	30
▽	n-decane	n-hexane	200	0.2	30
◇	No.2GT	n-hexane	20	0.2	30
▷	No.2GT	n-decane	20	0.2	30
△	No.2GT	n-decane	20	0.3	30
○	n-decane	n-hexane	20	0.2	28.5

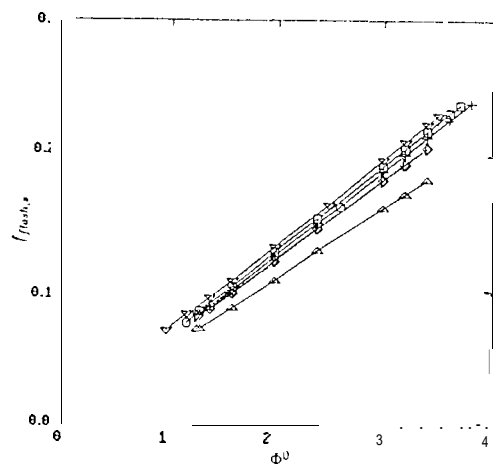


Fig.1 The solvent flash-flame burned fraction vs. air/fuel mass ratio

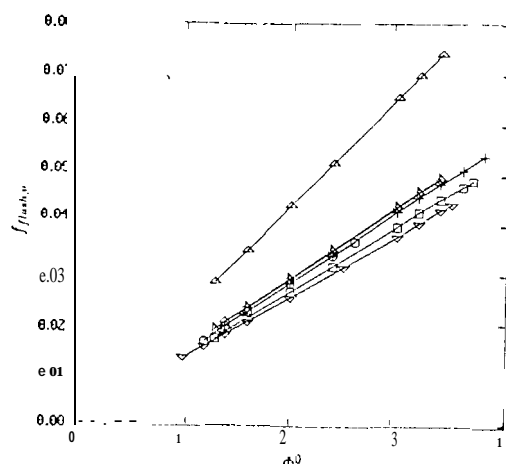


Fig.2 The solute flash-flame burned fraction vs. air/fuel mass ratio

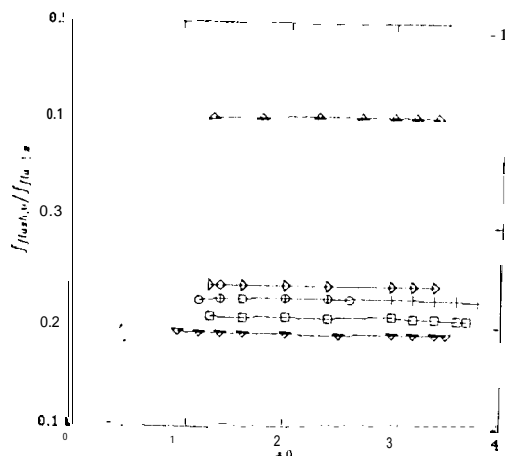


Fig.3 The ratio of flash-flame burned fractions vs. air/fuel mass ratio

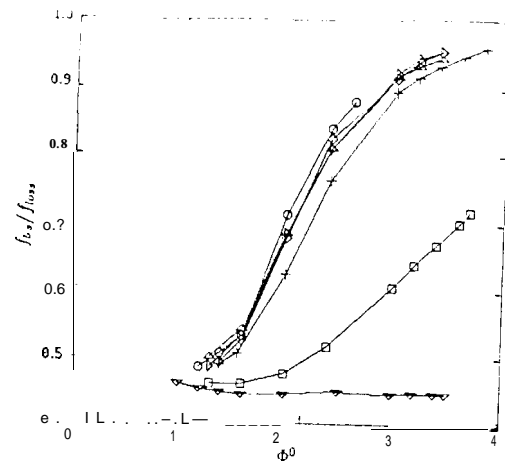


Fig.4 The ratio of lost to burned fractions for solvent vs. air/fuel mass ratio

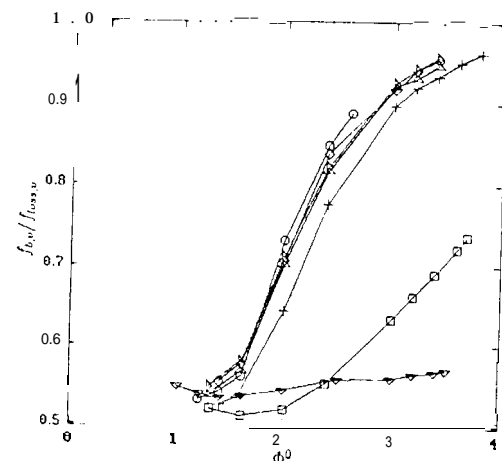


Fig.5 The ratio of lost to burned fractions for solute vs. air/fuel mass ratio

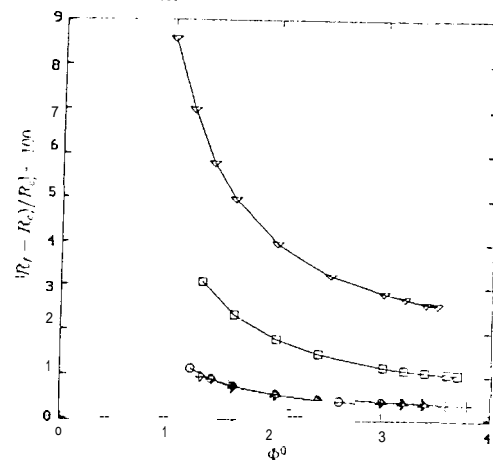


Fig.6 The nondimensional stand-off distance of the flame vs. air/fuel mass ratio

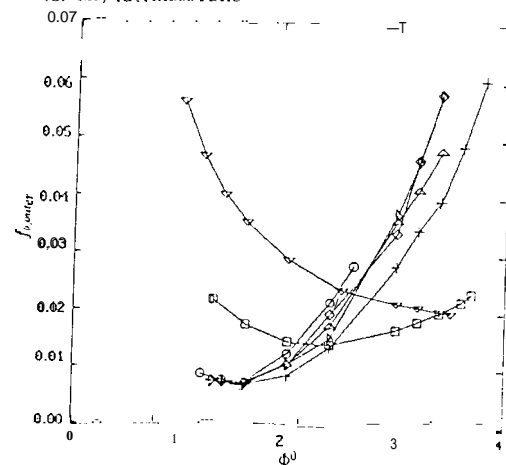


Fig.7 The fraction of fuel burned during outer cluster combustion vs. air/fuel mass ratio